Simulator Sickness Research Summary[1]

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Simulator Sickness (SS) is a form of Motion Sickness (MS) that does not require true motion – but does require a wide field of view (FOV) visual display [5, 46, 64]. Like all varieties of MS, an intact vestibular system is necessary to experience SS [12]. It has been called visually induced motion sickness [3, 52, 48] and Cinerama sickness [3, 5, 52]. The term "vection" is used to describe a visually induced sense of self-motion. Vection is "… produced by the nearly uniform motion of a large part of the visual field … When the entire field moves, subjects soon begin to feel that the relative motion is their own" (Young [64], p. 98). Whether found in a flight simulator, Cinerama theatre, IMAX theatre, or virtual reality simulation, vection causes a MS-like discomfort for a substantial minority of participants. This unpleasant experience is now universally referred to as SS. Further, these MS-like symptoms are now referred to as SS whether the simulator is a fixed-base model, and has no true motion, or a motion-base one with a (limited) range of movement. In other words, if the discomfort occurs in a simulator of any kind it will be called SS in the literature.

> Simulator sickness is a term used to describe the diverse signs or symptoms that have been experienced by flight crews during or after a training session in a flight simulator … Motion sickness is a general term for a constellation of symptoms and signs, generally adverse, due to exposure to abrupt, periodic, or unnatural accelerations. Simulator sickness is a special case of motion sickness that may be due to these accelerative forces or may be caused by visual motion cues without actual movement of the subject … (McCauley, [41], p. 1)

A subtle distinction has been made between true MS and SS. MS is caused by motion. SS is caused by an inability to simulate the motion environment accurately enough [23, 33, 48]. If a particular flight profile in an aircraft causes discomfort, this is MS. If the same profile is simulated veridically in a simulator, with the same physical forces present, and discomfort is caused, technically this is still MS. If a particular flight profile in the aircraft does not cause discomfort, but when simulated it does, this is SS. SS is discomfort produced in the simulator that does not occur when the same profile is executed in the physical motion environment. However, this is a logical distinction that apparently has no practical significance. As before, if the discomfort occurs in a simulator it will be called SS in the literature.

1.0 REVIEWS

This problem was duly noted and became the justification for increased research into the magnitude, correlates, causes, and treatment of SS. The results of this work have been reviewed extensively. Crowley and Gower [10] offered an introductory review for the experienced aviator. The excellent books edited by McCauley [41] and AGARD [1] reviewed key areas of this research. Reviews by Kennedy and colleagues described the earlier research with special emphasis on the large Navy database [23, 25, 29, 38]. With the emergence of virtual environment technologies and helmet-mounted displays in the 1990s, the salience of the problem of SS increased again – and this time not just for military training, but for consumer entertainment as

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well. Later reviews [5, 12, 26, 31, 48] expanded on the earlier reviews by including these newer technologies, where research was available, and addressing issues related to virtual reality. The detailed review by Wright [63] addressed the problem of SS in the training of Army helicopter pilots.

2.0 SELECTED HISTORY

Signs and symptoms of MS have been produced by visual stimulation alone in persons with an intact vestibular system. "This problem has been known to ophthalmologists and optometrists since the 1840s as the disorder termed asthenopia …" (Ebenholtz, [12], p. 302). Asthenopia remained a little-known optical disorder until 1956 when aviators began operating the first fixed-base (non-motion) helicopter simulator.

2.1 Miller and Goodson [44, 45]

Bell Aircraft Corporation was contracted by the Navy to develop a helicopter simulator for training visual flight skills and hovering. During preliminary demonstrations at Bell, prior to delivery to the Navy, it was found "… that a large number of observers (mostly helicopter pilots) experienced some degree of vertigo during these demonstrations" (Miller and Goodson, [44], p. 7). The observers commented that their discomfort stemmed from the lack of vestibular cues to motion available from the fixed-base device.

Upon installation at the Naval Air Station, Pensacola, two psychologists (Havron and Butler) conducted an initial training evaluation of the device. During this evaluation "… a questionnaire revealed that twenty-eight of thirty-six respondents experienced some degree of sickness" (Miller and Goodson, [44], p. 8). These participants included flight instructors, students, and other personnel experienced both in the simulator and the helicopter. "The more experienced instructors seemed to be the most susceptible to these unpleasant sensations" (Miller and Goodson, [44], p. 8). Sixty percent (60%) of the instructors reported SS symptoms, but only twelve percent (12%) of the students (Miller and Goodson, [45]). This SS usually occurred in the first ten minutes of a training session and frequently lasted for several hours afterward. The incidence and severity of this SS "… became such a serious problem that it was felt that unless it can be remedied in some way the utilization of such simulators as training devices would be limited considerably" (Miller and Goodson, p. 8).

As a part of their evaluation, Miller and Goodson [44] interviewed several of the instructors from the earlier Havron and Butler study. "One of these men had been so badly disoriented in the simulator that he was later forced to stop his car, get out, and walk around in order to regain his bearings enough to continue driving" (Miller and Goodson, p. 9). Miller and Goodson reported positive transfer of training from simulator to aircraft, albeit with a tiny sample size. Later Miller and Goodson conducted an experiment in an attempt to determine the effect of retinal disparity and convergence on SS in this device. They recruited 10 Navy enlisted men as participants. They were unable to find any effect of their independent variables upon SS and concluded that, due to large individual differences in the report of sickness, a "… great many more than ten subjects" (Miller and Goodson, p. 11) were needed to perform behavioral research on this phenomenon. They discussed problems with the device that caused several optical abnormalities. Specifically, Miller and Goodson [45] noted visual distortions and conflicts that could have caused the SS, including: blurring of the image, distorted size perspective, and distorted movement parallax. While Miller and Goodson concluded that the discomfort found could have been caused by some combination of conflicts within the visual modality alone, they also reported that an inter-sensory conflict between vision and proprioception existed. Finally, they listed a number of advantages to using a simulator for aircraft training, including: safety, weather independence, training for special missions, and large economic savings. However, the SS problem "… became so serious that it was one of the chief reasons for discontinuing the use of the simulator" (Miller and Goodson, p. 212).

The events described above represent the first published accounts of SS. Several of the issues identified at the dawn of SS research have remained issues throughout the history of the field. To wit:

1) A substantial percentage of the people who operate the simulator experience SS. This is not a trivial event for simulator-based training – especially for helicopter training.
2) The personnel with more experience in the aircraft appear to have an increased susceptibility to SS.
3) Conflicts both inter-sensory (visual/vestibular) and intra-sensory (visual/visual or vestibular/vestibular) are implicated as the cause of SS.
4) The aftereffects of SS can last for hours.
5) Unless remedied in some way, SS will limit simulator-based training.
6) The Miller-Goodson anecdote. "One of these men had been so badly disoriented in the simulator that he was later forced to stop his car, get out, and walk around in order to regain his bearings enough to continue driving." This anecdote has been repeated frequently throughout the literature as evidence that safety issues are at stake in simulator-based training.
7) Sample size matters. Individual differences in susceptibility to, and reporting of, SS are so large that behavioral research requires large sample sizes.
8) Research shows positive transfer of training from the simulator to the aircraft for many tasks.
9) There are many advantages to simulator-based training besides positive transfer of training, including: safety, independence from (non-flyable) weather, the opportunity to train special missions (mission rehearsal), and large savings in the resources required for flight training.

2.2 McGuinness, Bouwman, and Forbes [42]

The Air Combat Maneuvering Simulator (ACMS) was installed at the Naval Air Station, Virginia Beach, in November 1979; it was commissioned in February 1980; and by March of 1980 reports of SS had found their way to the Naval Training Equipment Center for investigation (McGuinness et al.). The ACMS was a wide FOV, fixed-base, fixed-wing aircraft simulator designed to resemble the cockpits of F-4 and F-14 fighters. Questionnaires were administered to 66 aviators during individual, confidential interviews. The aviators were either pilots or radar intercept officers with flight experience ranging from 250 to 4000 hours. Each had four one-hour training sessions in the ACMS over a period of approximately one week.

Twenty-seven percent (27%) of the participants experienced at least one symptom of SS. The rate for participants with greater than 1500 flight hours experience was 47%, while for those with 1500 or fewer hours it was 18%. The ages of participants were not reported, nor were the incidence rates presented by age. The most common symptom reported was dizziness, followed by vertigo, disorientation, and nausea. There were no reports of flashbacks. Of those who reported symptoms of SS, 61% stated that these symptoms persisted between 15 minutes and 6 hours. Of those who reported symptoms, all symptoms subsided completely after a night's rest. Thirty-three percent (33%) of the aviators reported that the reset function (freezing the visual display and returning to a new set of initial conditions) was the most probable cause of SS onset. There was some evidence of adaptation to the simulator over the course of several sessions. Finally, as a part of their literature review, the authors repeated the Miller-Goodson anecdote.

Several of the findings and explanations reported by McGuinness et al. [42] have been replicated or cited in many other articles since then. For example:

1) The authors explained the SS found in their study with reference to the sensory conflict theory. They argued that there was an inter-sensory conflict between the vection produced by the wide FOV visual display and the lack of any actual motion (vestibular stimulation) in the fixed-base simulator.

2) They explained the differential rate of SS as a function of flight experience, measured by flight hours, in the same fashion. The relative sensory conflict would have been greater for the more experienced aviators because these aviators had a larger neural store of prior flight experience. Therefore, a larger conflict between the current pattern of sensory inputs and the expected pattern would translate into more SS. However, unlike many later researchers, McGuinness et al. did not ignore age entirely. They cited a report by Olive stating that susceptibility to vertigo and disorientation increased with increasing age of Naval aviators. They also stated:

   Physiological body changes resulting from physical aging may also be a contributing factor to this phenomenon, since those with more flight hours naturally tend to fall into older age groups. (McGuinness et al., [42], p. 25)

3) The SS symptoms reported by the participants, though similar to MS symptoms, were not identical. There were more vision and disorientation symptoms and fewer gastrointestinal symptoms. That is, there was less nausea and no emesis.

4) The symptoms had abated after one night's rest.

5) The freeze/reset function was implicated as causal in producing SS.

6) There was some evidence of adaptation over repeated simulator sessions.

2.3 McCauley [41]

McCauley described several potential operational problems that could result from SS. This discussion (McCauley's four points) was quickly adopted and repeated by later authors.

1) Compromised Training. Symptoms experienced in the simulator may compromise training through distraction and decreased motivation. Behaviors learned in the simulator to avoid symptoms (e.g., not looking out the window, reducing head movements, avoiding aggressive maneuvers) may be inappropriate for flight.

2) Decreased Simulator Use. Because of the unpleasant symptoms and aftereffects, simulator users may be reluctant to return for subsequent training sessions. They also may have reduced confidence in the training they receive from the simulator.

3) Ground Safety. Aftereffects, such as disequilibrium, could be potentially hazardous for users when exiting the simulator or driving home.

4) Flight Safety. No direct evidence exists for a relationship between simulator sickness aftereffects and accident probability. However, from the scientific literature on perceptual adaptation, one could predict that adaptation to a simulator's rearranged perceptual dynamics would be counterproductive in flight.

(McCauley, [41], pp. 2-3)

These issues were discussed as potentially significant operational problems. For those who work in the field of simulator-based flight training, it is not a stretch to imagine that SS can affect safety and training. This possibility was noticed immediately (Miller and Goodson, [44, 45]). However, note that McCauley explicitly

stated that there was “no direct evidence” suggesting simulators are causally implicated in aircraft accidents. McCauley’s four points appear frequently in published reports of SS.

2.4 Crowley [9]

In August 1984 the AH-1 Cobra Flight Weapons Simulator (FWS) became operational at Hanau U.S. Army Airfield in Germany. Soon thereafter reports of pilots becoming ill were made to Dr. Crowley, a flight surgeon at Hanau. Crowley’s study was performed during the spring of 1985. The FWS was a motion-base simulator, employing a terrain board database, and moderately narrow FOV visual displays (48 degrees horizontal gunner station, 96 degrees horizontal pilot station). Anonymous questionnaires were administered to 115 Army Cobra pilots who were training using the FWS simulator at Hanau. One hundred twelve (112) questionnaires were returned (97%).

Forty percent (40%) of the participants reported at least one symptom of SS. Nausea was the most frequent symptom, followed by sweating, and dizziness. Three pilots (3%) reported vomiting. Pilots who reported SS symptoms had significantly more total flight time than those who did not report symptoms. Pilots with greater than 1,000 hours of Cobra flight time were significantly more likely to report SS than pilots with fewer than 1,000 hours. Experience in the FWS was significantly and negatively correlated with reported SS. That is, more simulator time in the FWS was associated with fewer reports of SS symptoms. Crowley (1987) explained these results in terms of the sensory conflict theory. He quoted the Miller-Goodson anecdote. He also discussed McCauley’s four points and observed that any negative effects of SS upon training remained to be documented.

Because Crowley believed SS to be a potential hazard to aviation safety, a mandatory grounding policy was instituted at Hanau Army Airfield. The most significant portions of the Hanau policy were:

> Aviators flying the AH-1 Flight Weapons Simulator (FWS) are medically restricted from flying duties until the beginning of the next duty day, (normally 0630-0730) … Any aviator forced to stop a simulator period early due to motion sickness is grounded until seen by a flight surgeon and returned to flying duty. (Crowley, [9], p. 357)

3.0 SIGNS AND SYMPTOMS

SS is polysymptomatic [26, 29, 30]. Symptoms include nausea, dizziness, spinning sensations, visual flashbacks, motor dyskinesia, confusion, and drowsiness [41]. Observable signs of SS include pallor, cold sweating, and emesis [41]. The standard measurement instrument for SS, the Simulator Sickness Questionnaire (Kennedy, Lane, et al.), lists 16 symptoms: general discomfort, fatigue, headache, eyestrain, difficulty focusing, increased salivation, sweating, nausea, difficulty concentrating, fullness of head, blurred vision, dizzy (eyes open), dizzy (eyes closed), vertigo, stomach awareness, and burping. Reports of visual flashbacks and visual hallucinations have been documented [41, 63, 64] although they are reported to be exceedingly rare.

The reader will note that the signs and symptoms of SS overlap with those described above for MS. There are several differences, however. The most consistently reported difference is that while major symptoms of MS involve gastrointestinal distress (e.g., burping, stomach awareness, nausea, emesis), for SS there are fewer gastrointestinal symptoms and more visual ones (e.g., eyestrain, difficulty focusing, blurred vision, headache) [23, 26, 30, 31, 38, 61]. Vomiting is a common sign of MS. For example, 75 percent of those suffering from seasickness vomit [26]. By comparison, vomiting is rare in SS – usually occurring in less than one percent (1%) of the cases [26, 30]. Finally, in cases of vection-induced SS, such as a fixed-base flight simulator, closing one’s eyes will end the perceived motion and dramatically reduce the symptoms [30]. Closing one’s eyes, however, will have no such effect on MS, as noted above.

Helicopter simulators have been widely reported to produce more SS than fixed-wing simulators [2, 23, 31, 32, 63, 64]. This is probably because helicopters are usually flown closer to the ground. Discomfort level varies inversely with height above terrain [26, 33, 63]. There is a greater perception of visual flow, caused by greater visual detail, at lower height above terrain.

Several reports of original research include a listing of the most common symptoms found in helicopter simulators. Gower and Fowlkes [14] reported a study of the Cobra AH-1 FWS. This device incorporated a six-degree of freedom (6-DOF) motion base. (These six dimensions of motion are pitch, roll, yaw, vertical [heave], lateral [sway], and longitudinal [surge]). The most commonly reported symptoms from Gower and Fowlkes were eyestrain (37% of the participants) and fatigue (27%).

Gower, Lilienthal, Kennedy, Fowlkes, and Baltzley [17] reported on another simulator of an attack helicopter. This was the Combat Mission Simulator for the Apache AH-64A. The CMS is an interactive, full-mission, 6-DOF simulator. The most commonly reported symptoms were fatigue (43% of participants), sweating (30%), and eyestrain (29%). Braithwaite and Braithwaite [6] reported on a simulator for the British attack helicopter the Lynx. This device included a 6-DOF motion system with a 130 degree (horizontal) by 30 degree (vertical) FOV color projection visual system. The most commonly reported symptoms were disorientation (24% of participants) and difficulty focusing (24%).

Gower and Fowlkes [15] studied the SS potential of a simulator for the UH-60 Blackhawk utility helicopter. This device incorporated a 6-DOF motion base plus forward, left, and right out-the-window views from a collimated visual display. The most common symptoms were fatigue (35% of participants) and eyestrain (34%). Silverman and Slaughter [57] reported on an operational flight trainer for the MH-60G PAVE Hawk helicopter. This was a fixed-base device. It provided a 150 degree (h) by 40 degree (v) out-the-window visual display plus two chin window displays. The most commonly reported symptoms were stomach awareness, dizziness, nausea, fatigue, and sweating in descending order of frequency.

Gower, Fowlkes, and Baltzley [16] reported on the SS symptoms produced by the full-mission simulator model 2B31 for the CH-47 Chinook cargo helicopter. This was a 6-DOF motion device with a 48 degree (h) by 36 degree (v) forward visual display plus a 22 degree (h) by 30 degree (v) chin window display. The most commonly reported symptoms of SS were fatigue (34% of participants), eyestrain (29%), headache (17%), difficulty focusing (13%), sweating (11%), nausea (9%), and stomach awareness (9%).

4.0 MEASUREMENT

Several reviews discussed the difficulties with and tools for measuring SS [7, 20, 26, 33]. Because SS is polysymptomatic one cannot measure just one dependent variable (Kennedy and Fowlkes). Another measurement difficulty is that there are large individual differences in susceptibility to SS. It is common in this research to find that fully 50 percent of simulator operators experience no symptoms at all (Kennedy and Fowlkes [26]). When effects of SS exist, they are often small, weak effects that disappear quickly upon exiting the simulator. Further, because most participants eventually adapt to the motion environment of a particular simulator, researchers cannot reuse the same participants (such as in a within-subjects research design). Thus, researchers are forced to employ between-subjects research designs (Kennedy and Fowlkes [26]). When one combines these factors of large individual differences, weak effects, adaptation, and between-subjects designs it invariably leads to the conclusion that research into SS requires large sample sizes. To get samples of this large size, researchers are forced to survey pilots training in simulators at military training centers (Kennedy and Fowlkes [26]). However, these military centers exist to train pilots efficiently

and effectively, not to perform research. This means that the level of experimental control exercised by a researcher is usually low. So research studies investigating SS are either vast surveys of nearly all pilots operating a particular simulator at a particular facility at a particular time, or small-scale experiments with rather more experimental control, but much smaller sample sizes.

There are a number of possible ways to measure SS [7, 20]. One could employ direct observation of participants during a simulator session and note signs such as facial pallor and sweating. This is seldom done for research measurement (cf., Uliano et al., [61]), but often used by instructors at the simulator site to monitor their students. Another option would be self-report measures, such as the Simulator Sickness Questionnaire, that ask the participant to note the type and severity of symptoms currently being experienced. This method is universally performed in some fashion. A third option would be to instrument the participants and measure physiological conditions such as respiration rate and stomach activity. This method has been used upon occasion. Finally, one can employ tests of postural equilibrium to measure simulator-induced disorientation or ataxia. These tests have been widely employed, but with equivocal results.

4.1 Simulator Sickness Questionnaire (SSQ)

The SSQ is currently the gold standard for measuring SS. This instrument was developed and validated by Kennedy, Lane, et al. [30]. The SSQ was developed based upon 1,119 pairs of pre-exposure/post-exposure scores from data that were collected and reported earlier (Baltzley et al., [2]; Kennedy et al., [32]). These data were collected from 10 Navy flight simulators representing both fixed-wing and rotary-wing aircraft. The simulators selected were both 6-DOF motion and fixed-base models, and also represented a variety of visual display technologies. The SSQ was developed and validated with data from pilots who reported to simulator training healthy and fit.

The SSQ is a self-report symptom checklist. It includes 16 symptoms that are associated with SS. Participants indicate the level of severity of the 16 symptoms that they are experiencing currently. For each of the 16 symptoms there are four levels of severity (none, slight, moderate, severe). The SSQ provides a Total Severity score as well as scores for three subscales (Nausea, Oculomotor, and Disorientation). The Total Severity score is a composite created from the three subscales. It is the best single measure because it provides an index of the overall symptoms. The three subscales provide diagnostic information about particular symptom categories. The Nausea subscale is made up of symptoms such as increased salivation, sweating, nausea, stomach awareness, and burping. The Oculomotor subscale includes symptoms such as fatigue, headache, eyestrain, and difficulty focusing. The Disorientation subscale is composed of symptoms such as vertigo, dizzy (eyes open), dizzy (eyes closed), and blurred vision. The three subscales are not orthogonal to one another. There is a general factor common to all of them. Nonetheless, the subscales provide differential information as to symptomatology and are useful for determining the particular pattern of discomfort produced by a given simulator. All scores have as their lowest level a natural zero (no symptoms) and increase with increasing symptoms reported.

An important advantage of the SSQ is that a wide variety of symptoms can be measured quickly and easily with the administration of this one questionnaire. Another important advantage is that it allows quantitative comparisons across simulators, populations, and within the same simulator over time (as a diagnostic to determine if recalibration is needed, for example).

However, Kennedy, Lane, et al., [30] stated restrictions in the use of the SSQ also. First, the SSQ is not to be used with participants who are in other than their usual state of health and fitness. The instrument was developed and validated based on data from healthy, fit pilots. Any scores obtained from participants who arrived for

simulator training ill would be uninterpretable. Second, the authors recommended that the SSQ be administered immediately after a simulator session, but not before one. They did not recommend using pre-post difference scores. This is because the high correlation usually found between pre and post can render the difference scores unreliable. Nonetheless, researchers are so comfortable with the SSQ that they sometimes report pre-post difference scores anyway (e.g., Regan and Ramsey, [53]).

4.2 Instrumented Physiological Measures

> Changes in bodily cardiovascular, gastrointestinal, respiratory, biochemical, and temperature regulation functions often arise with simulator sickness. Several physiological measures have been electronically or electro-optically instrumented and transduced directly from subjects in simulator experiments. (Casali and Frank, [7], pp. 9-10).

Heart rate, or pulse rate, has been reported to change from baseline levels as a function of simulator exposure [7]. Unfortunately these reported changes are not sensitive, reliable, or always in the same direction. Respiration rate has proven to be a sensitive index of SS (Casali and Frank). However, the direction of the change is not consistent across individuals. As with MS [52] some individuals increase respiration rate upon simulator exposure, while others decrease rate. Casali and Frank recommend using an absolute difference score. Sweating is a common symptom of SS and this can be measured as an increase in skin conductance or a decrease in skin resistance (Casali and Frank). Facial pallor is also a common symptom of SS. Paleness of the skin can be measured using photo-optical sensors and has been shown to vary as a function of conditions that cause SS (Casali and Frank). Gastric activity can be measured with an electrogastrogram. Gastric activity in the form of tachygastria, a dramatic increase in stomach motility, has been shown to occur along with other symptoms of SS during exposure to vection (Casali and Frank; Hettinger et al., [7]).

4.3 Tests of Postural Equilibrium

Reviews of this methodology can be found in Casali and Frank [7], Kennedy et al., [24], and Kolasinski [33]. Postural equilibrium tests (PETs) exist to provide a behavioral measure of ataxia. Ataxia is a potentially dangerous symptom of SS. It is usually defined generically as:

> An inability to coordinate voluntary muscular movements that is symptomatic of any of several disorders of the nervous system. (Merriam-Webster, [43], p. 137).
>
> Marked incoordination in voluntary muscular movements. (English and English, [13], p. 48).

In the domain of SS research, ataxia is defined as postural instability, postural unsteadiness, or postural disequilibrium (e.g., Kennedy et al., [24]; Kolasinski and Gilson, [35]). It is thought that any disruption of balance and coordination that results from exposure to a simulator may be a safety concern for pilots who need to walk, climb stairs, drive, or fly after a simulator training session. The PETs are used to provide a direct index of postural instability.

> Loss of balance and ataxia are common problems noted by trainees and subjects after exiting a dynamic simulator. The simulator presents an altered sensory environment which usually entails considerable vection, and some adaptation to this environment occurs in the operator's visual and vestibular sensory systems. Upon return to the "normal" environment, balance and equilibrium may be disrupted until the person progresses through re-adaptation. Such effects may be measured using pre-post simulator postural equilibrium tests. (Casali and Frank, [7], p. 14).

There are several PETs that are described in the literature. They all involve some permutation of the following procedures: standing heel to toe with eyes closed and arms folded across the chest or back; or standing on one leg (preferred leg or non-preferred leg) with eyes closed or open and arms folded across the chest; or walking a straight line (on floor or rail) heel to toe with eyes closed or open and arms folded across the chest. The names and acronyms, where available, for several PETs are listed: Sharpened Romberg (SR), Stand on One Leg Eyes Closed (SOLEC), Stand On Preferred Leg Eyes Closed (SOPLEC, SOPL), Stand On Non-preferred Leg Eyes Closed (SONLEC, SONL), walk toe to heel, Walk On Floor Eyes Closed (WOFEC), Walk On Line Eyes Closed (WOLEC), and Walk On Rail Eyes Open (WOREO).

An example of a method for using PETs in research is described below:

> Standing on Preferred Leg (SOPL): This test of standing steadiness required pilots to first determine which leg they preferred to stand on. Pilots were asked to stand, fold their arms against their chest, close their eyes, lift their non-preferred leg and lay it about two-thirds of the way up the standing leg's calf. They attempted to remain in that position for 30 s. If they moved their pivot foot, moved their raised foot away from their standing leg, grossly lost their erect body position, the trial ended and the time up to that point (in seconds) was recorded as the score for that trial.
>
> Standing on Non-Preferred Leg (SONL): The procedure for this test was identical to that of the SOPL test except that pilots stood on their non-preferred leg. (Kennedy et al., [24], p. 15).

The research literature shows mixed results when using PETs to demonstrate an effect of simulator exposure upon postural stability. Some studies have found no statistically significant effect of simulator exposure upon performance of PETs [15, 16, 18, 36, 61]. Other studies have found a statistically significant effect for some or all PETs used [11, 14, 17, 24, 37, 62].

There are several differences among the reports cited above. Nonetheless possible explanations for these equivocal results present themselves. As mentioned above with regard to SS in general, if an effect is highly subject to individual variability then large sample sizes are required. The mean sample size for the five studies listed above that did not report a significant difference was 61. For the six studies that reported positive results the mean sample size was 120. One cause of variability in performance can be differential rates of learning. Hamilton et al. [18] demonstrated significant learning effects in the performance of four PETs (SR, SOLEC, WOREO, WOLEC). Further, performance on these four PETs continued to improve over the 10 practice sessions they measured. Therefore, when using PETs one must be aware that any improvement in performance occasioned by learning will tend to mask any decrement in performance caused by simulator exposure – if such a decrement exists.

Finally, Kennedy et al. [24] found a statistically significant correlation between the disorientation subscale of the SSQ and performance measures taken from two PETs (SOPL, SONL). The higher the disorientation scores on the SSQ, the poorer the performance on the two PETs. In other words, the subjective self-reports of the pilot participants accurately reflected the behavioral measures taken from them after exiting the simulators. Given the potential measurement problems associated with PETs, the time and effort required in their administration, and the fact that similar results can be acquired more easily and quickly with the SSQ, the use of tests of postural equilibrium should probably be limited to research questions where their specific contribution is necessary.

5.0 INCIDENCE

The incidence of SS varies widely across simulators and conditions. A common method of presenting incidence is to list the percentage of participants who reported at least one symptom. In the review by McCauley [41]

incidence was reported to range from 10 to 88 percent. In their review Kennedy and Frank [29] reported that incidence ranged from 27 to 88 percent. In later reviews Kennedy and colleagues [25, 26] reported that the incidence of SS ranged from 12 to 60 percent in Navy flight simulators. Pausch et al., [48] reported in their review that it could range from 0 to 90 percent in flight simulators. Wright [63] limited his review to helicopter flight simulators. He reported that the incidence ranged from a low of 13 percent, when a strict criterion was employed to define SS, to a high of 70 percent, when a lax criterion was used.

It is widely reported that simulators of rotary-wing (RW) aircraft cause participants more SS than simulators of fixed-wing (FW) aircraft. Assuming a constant criterion of at least one reported symptom, there are several studies that report incidence by simulated aircraft type. Kennedy and colleagues [23, 32] collected data from 1,186 simulator exposures. Their sample included data from 10 flight simulators. These simulators represented both FW and RW aircraft, and included both motion-base and fixed-base models. The incidence rates for FW simulators ranged from 10 to 47 percent. The rates for RW simulators ranged from 26 to 69 percent. Baltzley et al., [2] collected data from 742 exposures using a self-report questionnaire. Their sample included data from operators of 11 flight simulators (7 FW, 4 RW). All participants had experience training in flight simulators. The incidence rates reported by pilots training in FW simulators ranged from 6 to 62 percent. The rates reported by pilots training in helicopter simulators ranged from 48 to 57 percent. These results have the advantages of large sample sizes, multiple flight simulators, and a constant method of research and analysis performed by the same investigators.

Magee, Kantor, and Sweeney [40] collected data from a sample of 42 C-130 pilots and flight engineers. The C-130 Hercules is a multi-engine, propeller-driven, FW, cargo aircraft. The C-130 simulator included a 6-DOF motion base and a 120 degree (h) by 40 degree (v) FOV visual display. Participants performed a four-hour simulator session with a short break at the mid-point. Ninety-five percent (95%) of the participants reported at least one symptom of SS upon exiting the simulator.

Crowley reported an incidence rate of 40 percent for the RW Cobra FWS. Braithewaite and Braithewaite [6] reported an incidence rate of 60 percent for 183 Lynx helicopter crewmembers that returned self-report questionnaires. Gower et al., (1987) collected data from 127 participants training in the AH-64 CMS. This simulator represents the AH-64A Apache helicopter. An incidence rate of 44 percent was reported. Gower and Fowlkes [14] collected data from 74 Army aviators training in the Cobra FWS. Thirty-seven percent (37%) of the participants reported at least one symptom of SS. All four of the studies described in this paragraph reported results obtained from participants operating 6-DOF motion-base devices that simulated attack helicopters.

Lerman et al. [37] collected data from 59 armor Soldiers performing tank driver training in a 3-DOF (pitch, roll, yaw) tank simulator. Sixty-eight percent (68%) of this sample reported at least one symptom of SS. Using the SSQ, Lampton et al. [36] measured SS in an M-1 tank driver simulator mounted on a 6-DOF motion platform. They also measured discomfort in the actual M-1 tank. The authors reported significantly greater symptom scores in the simulator than in the tank. Upon interview, thirty-six percent (36%) of their sample reported experiencing discomfort in the simulator. The authors also reviewed the training records of six armor companies that had experienced the device previously. They found that 25 percent of these training records documented SS among the prior trainees. It is plausible that these incidence rates reported by Lampton and colleagues are conservative estimates. Instructors are not likely to mention SS in a written training document unless it is a significant phenomenon.

SS also exists in virtual reality (VR) simulators. For a review of SS from this perspective see Kolasinski [33]. Regan and Ramsey [53] reported a 75 percent incidence rate for subjects in the placebo control group of a VR

drug experiment. This level of discomfort was produced by a 20-minute immersion in the VR simulator. Kolasinski and Gilson [35] immersed 40 research participants in a commercially available VR simulator for 20 minutes. Eighty-five percent (85%) of the participants reported at least one symptom of SS. It was because of high sickness rates such as these, produced by relatively short simulator sessions, that the practical future of VR technology became a subject of discussion (e.g., Biocca, [5]; Kolasinski, [34]; Pausch et al., [48]).

It is clear from the literature reviewed above that the incidence of SS varies within a large range. Depending upon the simulator, the conditions of operation, and the criterion definition applied, the rate of SS can vary from low to extremely high.

6.0 RESIDUAL AFTEREFFECTS

The potential for dangerous aftereffects of simulator exposure – including ataxia, loss of balance, flashbacks – has been noted right from the beginning [44, 45]. In fact, the careful reader will meet the Miller-Goodson anecdote frequently in the literature – either quoted directly (e.g., Crowley, [9]; McCauley, [41]; McGuinness et al., [42]; Pausch et al., [48]; Wright, [63]) or, more often, referred to obliquely. McCauley's four points – two of which concern safety – are ubiquitous. Virtually every report refers in some way to these points, usually in the introductory section. So researchers have done their part to alert the community of the potential for dangerous aftereffects of simulator-based flight training.

However, it is only prudent to assure the reader that this potential danger has not manifested itself objectively. Many of the same authors reported that there were no documented cases of flight incidents or automobile accidents linked to prior simulator-based training [9, 29, 41, 63]. The present author has performed a follow-up study on several hundred simulator-trained Apache pilots [21]. Not one aviator has reported an automobile or motorcycle accident within 12 hours of exiting the simulator.

Baltzley et al. [2] reported data from a large study involving 742 simulator exposures across 11 Navy and Army simulators. Overall, 45 percent of the participants reported experiencing symptoms of SS upon exiting the simulator. Of these pilots who reported symptoms, 75 percent said that their symptoms disappeared within 1 hour. Six percent (6%) reported that their symptoms dissipated in 1 to 2 hours, 6 percent in 2 to 4 hours, 5 percent in 4 to 6 hours, and 8 percent reported that their symptoms lasted longer than 6 hours. The most common category of aftereffect was nausea (51%), followed by disorientation (28%), and oculomotor (21%).

Braithwaite and Braithwaite [6] reported that 17 percent of their sample experienced aftereffects. The most frequently stated aftereffects were nausea, which dissipated in 2 hours, and headache, which sometimes lasted as long as 6 hours. Crowley [9] reported that 11 percent of his sample experienced delayed effects of simulator training. The most commonly reported delayed symptom was a perception of illusory movement. Gower et al. [17] reported aftereffects following training in the Apache CMS. Over a series of 10 training sessions, preflight minus postflight performance on 3 PETs decreased until session number 4 and then remained stable for the remainder of the simulator periods. This was interpreted as behavioral evidence of increasing simulator-induced disequilibrium over training trials.

McGuinness et al. [42] reported that 18 members of their sample of 66 aviators (27%) experienced at least one symptom of SS. Of these 18, 11 (61%) stated that their symptoms persisted anywhere from 15 minutes to 6 hours. Silverman and Slaughter [57] reported results from participants operating a wide FOV, fixed-base MH-60G operational flight trainer for the PAVE Hawk helicopter. Data were collected in conjunction with an operational test and evaluation of the simulator. Sortie lengths were at least 3 hours and included a full range of flight tasks. A total of 13 experienced aviators participated and filled-out self-report questionnaires.

Eight (8) of these 13 participants (62%) reported at least one symptom aftereffect. The most commonly reported aftereffects were fatigue, stomach awareness, and vertigo, in that order. Most of these aftereffects came and went within 2 hours of exiting the simulator, although some participants reported symptoms lasting up to "… several hours after the simulator training session" (Silverman and Slaughter, p. 11).

There are some crude conclusions that emerge about the aftereffects of simulator exposure. First, approximately 10 percent of the sample will experience pronounced aftereffects [23, 26]. Second, there is a significant positive correlation between the number and severity of symptoms reported immediately upon leaving the simulator, and the duration and severity of aftereffects [8, 57]. That is, those who experience the most SS during the simulator session usually experience the most aftereffects later. Third, the aftereffects of simulator exposure usually wear off in an hour or two. The persistence of symptoms longer than 6 hours has been documented repeatedly, but fortunately remains statistically infrequent.

It is understood in the training community that a potential exists for residual aftereffects to be a risk to flight safety. For this reason, guidelines recommending a mandatory grounding policy after training in a flight simulator have appeared both in the research literature and the training environment [8, 9, 10, 23, 25, 31, 38, 47]. The minimum recommended period from simulator to aircraft has ranged from 6 to 12 hours and usually includes the admonition to wait until the next day. In cases of severe discomfort, temporary curtailment of other duties for up to 24 hours has been recommended [23]. Currently in the U.S. Army, the policy on how much time must elapse from the end of a simulator training session to flight duty is a matter of unit standard operating procedure and is set by the unit commander [55]. At USAAVNC there is currently no regulation that restricts simulator-to-aircraft time – except for the Longbow Crew Trainer where the required delay is 1 hour [55].

> Allowing a night's sleep before recommencing flying duties should reduce residual risks to negligible proportions. (Chappelow, [8], p. 10).
>
> During initial simulator training sessions or after a long period of not using the simulator, avoid scheduling simulator and aircraft flights on the same day. (NTSC, [47] p. 8).

7.0 ADAPTATION

The concept of adaptation in the literature of SS is identical to that in the literature of MS. Several reviewers have discussed adaptation to a novel simulated motion environment [5, 10, 26, 29, 33, 63]. The theoretical approach used to explain the fact that most participants adapt to the simulator after approximately six sessions (Biocca; Wright) is the sensory conflict theory.

Crowley [9] found that there was a statistically significant inverse relationship between the prior number of hours spent training in the Cobra simulator and the amount of SS reported. The more prior exposure to the simulator, the less SS experienced currently. This was interpreted as evidence of adaptation. Gower and Fowlkes [14] reported the same inverse relationship with a different sample of Cobra pilots and another FWS. Gower et al. [16] reported a significant negative correlation between prior history of hours spent training in the CH-47 flight simulator and SS for a sample of experienced CH-47 pilots. Gower et al. [16] investigated the effects of exposure to the AH-64A CMS on discomfort levels for 127 Apache aviators. Over the course of 10 training sessions, they found that self-reported SS symptoms decreased with increasing sessions in the CMS. They also reported an inverse relationship between the amount of simulator exposure during the prior 3 months and SS. Finally, they noted a significant negative correlation between the amount of recent CMS exposure and disequilibrium as measured by a PET. These results were interpreted as evidence of adaptation to the CMS.

Silverman and Slaughter [57] reported evidence of adaptation to a MH-60G operational flight trainer for the PAVE Hawk helicopter. A sample of 13 experienced pilots executed a full range of flight tasks over several sessions in the simulator. The number of SS symptoms reported on later days were significantly fewer than the number reported on the first day of testing. Uliano et al. [61] required 25 experienced pilots to operate the Vertical Take-off and Landing (VTOL) simulator which represents the SH-60B Seahawk helicopter. Each pilot flew the same flight paths, and performed the same tasks under the same experimental conditions, in counter-balanced order, over 3 days. SS was reported to be significantly worse on day 1 than day 2, and significantly worse on day 2 than day 3. The authors interpreted these results as evidence of adaptation to the simulator.

Besides reviewing the SS literature, Wright [63] reported on his interviews with Army helicopter flight instructors. These instructors trained helicopter pilots daily. Yet, when introduced to a new simulator, they experienced SS symptoms. After a few days the symptoms disappeared or at least subsided to a minor and tolerable level. These instructors also reported that after several months away from the simulator, they had to readapt as if for the first time. Then readapt they did, again, in a few sessions. Wright interpreted these statements as evidence of adaptation to a novel (simulated) motion environment.

All of the studies cited above involved aviators adapting to a helicopter flight simulator of some kind. Lampton et al. [36] reported evidence of adaptation to an M-1 tank driver trainer. They collected data from 115 trainees, all of whom had no prior experience driving a tank. Over the course of several training sessions the amount of SS the trainees experienced decreased. The symptom scores, as measured using the SSQ, were significantly higher after the first training session than after the remainder of the sessions. These results were interpreted as adaptation to the simulator.

Reports and manuals that provide guidelines for the detection and treatment of SS acknowledge adaptation as the best current solution to the problem of simulator-induced discomfort (e.g., Kennedy et al., [25] ; Lilienthal et al., [38]; NTSC, [47]). As with MS, almost all participants eventually adapt to a simulated motion environment. Guidelines often describe procedures to employ during simulator-based flight training to encourage a rapid and reasonably comfortable adaptation period. For example:

> Adaptation of the individual is one of the strongest and most potent fixes for simulator sickness … Do not schedule simulator hops for greater than two hours for any reason. (Kennedy et al., [25], pp. 12, 17).
>
> Persons new to the simulator, and particularly persons with extensive flight time, are at most risk … Decrease the field of view during nauseogenic hops (e.g., initial hops) … Go on instruments. (Lilienthal et al., [38], pp. 277, 279).
>
> Brief simulator flights (short hops with gentle maneuvers) separated by one-day intervals will facilitate adaptation to simulator motion and help prevent sickness, especially during the early stages of simulator training for novices and for experienced pilots with little simulator training … Do not slew while the visual scene is turned on … If all else fails, turn off the motion base or the visual scene and conduct instrument training. (NTSC, [47], pp. 6-7).

8.0 SUSCEPTIBILITY

SS is not only polysymptomatic; it is polygenic [26, 29]. Kennedy and Fowlkes [26] listed 13 factors that are implicated in causing SS. These factors were subdivided into three categories: individual variables, simulator variables, and task variables. In an exhaustive review, Kolasinski [33] described 40 factors that are associated

with SS – also categorized as individual, simulator, and task variables. Pausch et al. [48] reviewed several factors that evoke SS, with special emphasis given to simulator design issues.

8.1 Gender

As with MS (e.g., Reason and Brand, [52]), reviews of SS reported that females are more susceptible than males (e.g., Biocca, [5]; Kennedy and Frank, [29]; Kolasinski, [33]; Pausch et al., [48]). The precise reason for this is unknown. Reviewers have cited at least three possible explanations: hormonal differences, FOV differences, and biased self-report data. The hormonal hypothesis is the same as that advanced in the MS literature – females are more susceptible to SS during a portion of their menstrual cycle. This hypothesis is not without its doubters (e.g., Biocca; Pausch et al.). More likely, some think, is the fact that females have a larger effective FOV, and larger FOV is associated with greater SS (e.g., Biocca; Kennedy and Frank; Pausch et al.). Finally, those data upon which gender differences are based are self-reports. Males, it is suggested, may be more likely to under-report the severity of their discomfort (e.g., Biocca; Kolasinski).

However explained, reports of gender differences in SS continue to emerge. Hein [19] reported the results of 22 separate studies, involving 469 participants, over the course of 6 years. All studies took place in a fixed-base, automobile-driving simulator. Hein stated that gender differences in susceptibility to SS were among the most consistent results. "At all ages, female drivers are more susceptible than male drivers" (Hein, p. 610).

8.2 Age

> Walt Disney World's "Mission: Space" thrill ride left some older riders gulping, "Houston, we have a problem." In the past eight months, six people over 55 have been taken to the hospital for chest pain and nausea after going on the $100 million ride … It is the most hospital visits for a single ride since Florida's major theme parks agreed in 2001 to report any serious injuries to the state … Last December, Disney began placing barf bags in the ride … (Schneider, [56], p. B2).

Reviewers have reported that susceptibility to SS varies with age in the same way that MS varies with age (e.g., Biocca, [5]; Kennedy and Frank, [29]; Kolasinski, [33]; Pausch et al., [48]; Young, [64]). That is, below age 2 infants are generally immune. Susceptibility is at its highest level between ages 2 and about 12. There is a pronounced decline between ages 12 and 21. This decline continues, though more slowly, through adulthood until about age 50, after which SS is very rare. These claims are based on the self-report data reviewed by Reason and Brand [52] for MS.

Perhaps the reason reviewers are forced to report conclusions based on decades-old self-report surveys of MS symptoms, is because so little research has been performed examining the effect of age on susceptibility to SS. Very few researchers have attempted to investigate the relationship between age and SS more directly. Braithwaite and Braithwaite [6] administered questionnaires to 230 pilots attending training in a simulator for the Lynx attack helicopter. All were males. Age ranged from 23 to 42 years with a mean age of 32. There was no relationship found between age and reported SS.

Warner et al. [62] assessed SS in two wide-FOV F-16 flight simulators. Twenty-four (24) male pilots participated in total. Sixteen (16) were active-duty military pilots of mean age 28.6 years (the "younger group"). Eight (8) were older active-duty military pilots and former military pilots of mean age 52.1 years (the "older group"). The task was a challenging 50-minute flight through a long, narrow, twisting canyon in each of the two simulators, in counter-balanced order, two weeks apart. One pilot from the younger group (1/16 = 6.25%) terminated a session prematurely due to severe SS. Three pilots from the older group

(3/8 = 37.5%) terminated a session prematurely due to severe SS. The discomfort ratings (early version SSQ) collected from pilots who terminated prematurely were significantly higher than those from pilots who completed the flight. Among those pilots who completed the flight, there was no significant difference in discomfort ratings between the younger and older groups. Among those pilots who completed the flight, there was also no significant difference in postural equilibrium (SOLEC, WOFEC) between the groups.

Hein [19] reported the results of 22 separate studies, involving 469 participants of both genders and a wide range of ages, over the course of 6 years. All studies took place in a fixed-base, automobile-driving simulator. Hein stated that age differences in susceptibility to SS were among the most consistent results. "Younger, male drivers adapt easily. Older drivers and women are severely susceptible to simulator sickness" (Hein, p. 611).

8.3 Age and Experience

Among those (like the present author) who have been involved in the simulator-based training of large numbers of aviators, it is common knowledge that older participants are more susceptible to SS. Further, the small amount of evidence that does exist tends to support these anecdotal observations. Yet researchers investigating SS rarely even aggregate their data by age. Given the importance of age in both behavioral science and medical science research, this appears to be a glaring omission. Then, to confuse matters further, reviewers of the SS literature continue to repeat the conclusions published by Reason and Brand [52] that sickness decreases with age and eventually almost disappears. Why is this so?

This is because researchers are convinced that the demographic variable that influences aviator SS is experience as measured in flight hours, not chronological age. Data are frequently aggregated by the flight hours of the participants. Researchers reviewing the literature discuss the impact of aircraft flight experience on SS. This view is also entirely consistent with the sensory conflict theory, where experience in a particular motion environment is central to the explanation.

However, among aviators age (in years) and experience (in flight hours) are strongly linked. Magee et al. [40] reported a statistically significant correlation between age and flight hours ($r = 0.67$). The present author [21] has also found a significant correlation ($r = 0.75$) between these variables. This is because "As is common in most professions, piloting experience tends to accumulate with age" (Tsang, [60], p. 525). Thus, disentangling age from experience is a knotty problem when examining SS among aviators (see [60]).

It would not, in principle, be such a difficult problem to assess the effect of age upon SS if non-aviators were used as research participants. The present author predicts that among adult non-aviators, SS will increase with age rather than decrease. The chief methodological problems to be solved in order to perform this research would be practical ones. First, gaining access to a sufficiently large sample of non-aviators of a wide range of ages. Second, gaining access to a flight simulator for a period of time sufficient to collect the requisite large amount of data.

8.4 Experience

It is universally understood within this research community that the more experienced aviators are more susceptible to SS than novices. For example, this understanding has been acknowledged in at least 12 reviews covering the period from 1984 to 2003 [4, 10, 25, 26, 29, 33, 38, 41, 46, 48, 63, 64]. In addition, some empirical evidence of this relationship has already been described earlier in the reports by Crowley [9], McGuinness et al. [42], and Miller and Goodson [44, 45].

Braithwaite and Braithwaite [6] found a statistically significant positive correlation between experience as measured in flight hours and SS among pilots training in a Singer-Link simulator for the Lynx attack helicopter. That is, pilots with a greater number of flight hours reported greater SS. Gower and Fowlkes [15] assessed SS (early version SSQ) among 87 Army aviators training in a UH-60 helicopter simulator. They found a significant positive correlation between flight hours and SSQ scores. Gower et al. [16] collected data from 57 aviators with flight experience ranging from 450 to 7,000 flight hours. The pilots were taking currency and refresher training in a 2B31 simulator for the CH-47 cargo helicopter. The authors found no correlation between flight hours and SSQ scores. Gower et al. [16] assessed SS among 127 Apache aviators with flight experience ranging from 150 to 8,400 flight hours. All pilots were training in the AH-64 CMS built by Singer-Link. Again, the authors found no significant correlation between flight hours and reported SS symptoms.

Magee et al. [40] assessed SS among a group of 42 male C-130 pilots and flight engineers operating a CAE C-130 simulator. Twenty-six (26) participants (the "experienced group") had flight hours ranging from 845 to 10,000 (median 3,166). Sixteen (16) participants (the "novice group") had flight hours ranging from 50 to 4,340 (median 1,465). There was no significant difference between the two groups in measured SS, either immediately after the simulator session or later. Also, a partial correlation of flight hours against measured SS, with age held constant, showed a small (0.03) and statistically insignificant result.

Silverman and Slaughter [57] collected data from 13 aviators as part of an operational test of a MH-60G PAVE Hawk simulator. The participants' total flight experience ranged from 350 to 15,327 hours. The authors reported that there was no statistically significant correlation between reported SS and either total flight hours or flight hours for the specific MH-60G helicopter. Uliano et al. [61] assessed SS among 25 male helicopter pilots. Their flight experience ranged from 360 to 2,860 hours (mean 1,071). All participants operated the VTOL simulator, which represented the SH-60B Seahawk helicopter. Aviators with fewer than 900 flight hours experience reported significantly less SS on all measures than those with 900 or more flight hours.

Lerman et al. [37] collected data from 59 male armor Soldiers operating a tank driver trainer. The authors found no significant correlation between amount of prior tank driving experience and SS symptoms.

Sensory conflict theory states that SS is caused when there is a difference between the current pattern of sensory information and what is expected on the basis of past experience. Thus, this theory predicts that the more flight experience an aviator has acquired, the greater will be the disparity between his or her neural store and the pattern presented by the flight simulator – since a simulator cannot perfectly simulate flight – and the more SS will be reported. This is the explanation given when statistically significant differences are found between highly experienced aviators and novices or students.

8.5 Prior History of Motion Sickness

Generally speaking, in the behavioral sciences past behavior is the best predictor of future behavior. It follows that people who have a history of prior episodes of MS or SS will be more likely to experience SS in future simulator-based training. Two reviewers reported that there is empirical evidence in support of this generalization [25, 63]. Kennedy, Fowlkes, et al. [27] discussed some of the methodological issues involved in using the Motion History Questionnaire (MHQ) to predict sickness scores in a simulator.

Braithwaite and Braithwaite [6] reported that among their sample of helicopter pilots training in a Lynx simulator, there was a significant positive correlation between self-reported prior history of motion sickness (MHQ) and SS. That is, those with a history of MS were more likely to experience SS in the helicopter simulator. Gower and Fowlkes [14] reported a significant positive correlation between past history of MS as

reported on the MHQ and reported SS while training in the Cobra FWS. Gower and Fowlkes [15] also reported a significant positive correlation between reported history of MS (MHQ) and SS among helicopter pilots training in a UH-60 simulator. Gower et al. [16] found this same statistically significant relationship between MHQ scores and early-version SSQ scores for aviators training in a simulator for the CH-47 cargo helicopter.

Gower et al. [16] collected data from 127 rated aviators training in the AH-64 CMS. They found a significant positive correlation between prior history as reported on the MHQ and SS as reported on a MS questionnaire. Kennedy et al. [23] reported the results of surveying 1186 pilots training in 10 Navy simulators. Five of the simulators were FW and five were RW. They reported a small but statistically significant, positive correlation between MHQ scores and SS symptoms. Warner et al. [62] did not find any significant relationship between MHQ scores and SS symptoms for 24 pilots operating two F-16 simulators. Twenty-four (24) participants, however, is usually too small a sample size for a meaningful study of the correlates of SS.

Lampton et al. [36] reported this same relationship for a sample of 115 male trainees operating an M-1 tank driver simulator. Trainees were asked, "Have you ever experienced motion sickness (such as in a car or bus, on a plane or train, on an amusement park ride, seasickness, etc.)?" Twenty-two percent (22%) responded in the affirmative. Those answering yes were significantly more likely to score higher on the SSQ. Lerman et al. [37] assessed 59 male armor Soldiers during tank driver training in a Link tank simulator. The authors reported a significant positive relationship between prior history as measured by the MSQ and SS as measured by a MS questionnaire.

To summarize, two reviewers as well as eight of nine research studies document that a prior history of MS is positively correlated with SS. Past behavior is the best single predictor of future behavior.

8.6 Miscellaneous: Illness, Drugs, Sleep, Fatigue

There are several health-related conditions that are known to influence susceptibility to SS. As with MS, there is the pathology of an absent or non-functional vestibular system. Persons with this pathology ("labyrinthine defectives") are incapable of experiencing either MS (e.g., Benson, [3]; Reason and Brand, [52]) or SS (e.g., Kennedy and Frank, [29]; Pausch et al., [48]).

It is widely understood among the research community that individuals should not participate in simulator-based training unless they are in their usual state of health and fitness. Individuals in ill health are more susceptible to SS (e.g., Kennedy et al., [25]; Kennedy and Fowlkes, [26]; Kolasinski, [33]; McCauley, [41]; NTSC, [47]; Pausch et al., [48]; Wright, [63]). Symptoms that make individuals more vulnerable include hangover, flu, respiratory illness, head cold, ear infection, ear blockage, and upset stomach. Individuals exhibiting these symptoms should not participate in simulator-based training or simulator-based research [30]. Similarly, it is widely known that certain medications, drugs, and alcohol can increase an aviator's susceptibility to SS (e.g., Biocca, [5]; Kennedy et al., [25]; Kennedy and Fowlkes [26]; NTSC [47]; Young, [64]).

Reviewers have stated that fatigue and sleep loss also predispose an individual to SS (e.g., Kennedy et al., [25]; NTSC, [47]; Pausch et al., [48]; Wright, [63]). Gower and colleagues (Gower and Fowlkes, [14]; Gower and Fowlkes, [15]; Gower et al., [16]) have repeatedly reported a significant inverse relationship between the numbers of hours slept the previous night and SS as measured on an early version of the SSQ. That is, the fewer the hours slept, the greater the SSQ score. Gower et al. [16] reported a significant negative biserial correlation between self-reported "enough sleep" (yes or no) and SS. That is, those aviators who reported that they had not had enough sleep last night, scored higher on the SSQ. This relationship between fatigue/sleep and SS is no trivial result. In military aviation training it is common for aviators to be less than fully rested during initial, advanced, or recurrent training.

8.7 Simulator Variables

There are several simulator factors that have been implicated as causal in SS. Arguably the two most thorough reviews of these factors can be found in Kolasinski [33] and Pausch et al. [48]. The review presented below is not an exhaustive listing of known simulator variables.

Wide FOV visual displays have long been associated with increased susceptibility to SS [19, 26, 33, 41, 48]. This is because with a wider FOV there is a greater perception of visual flow or vection. Another visual factor with a long history of association with SS is known as off-axis viewing, design eye point, or viewing region [26, 33, 41]. Every visual flight simulator has a design eye point. This is the location within the cockpit where the visual display can be viewed best and where the pilot should keep his or her head positioned. Moving one's head away from the design eye point, or optimal viewing region – by slouching or leaning forward, for example – will not only guarantee a poorer visual image, but will increase one's likelihood of experiencing discomfort. Perhaps the oldest visual factor known to evoke SS (e.g., Miller and Goodson, [44, 45]) is optical distortion caused by misaligned or poorly calibrated optics [12, 26, 33, 37, 41]. Finally, the general issue of cue asynchrony (visual delay, transport delay, asynchronous visual and motion systems) has been investigated as a source of SS, but with equivocal results [19, 33, 41, 48, 61].

8.8 Task Variables

Not surprisingly, what the participant does while in the simulator, and what is done to him or her, can have a marked impact upon susceptibility to SS. These task factors were particularly well presented in the reviews by Kolasinski [33] and McCauley [41]. The review of task variables presented below is not exhaustive.

First in importance is session duration [14, 16, 26, 33, 41, 63]. The longer the period of time spent operating the simulator, the greater the likelihood of significant discomfort. Another important factor is use, by the instructor, of the freeze/reset command [16, 17, 26, 33, 41, 63]. The more often the instructor freezes the pilot in mid-flight – to prevent a crash or provide instruction, for example – the more likely the pilot will experience SS. Other unusual or unnatural maneuvers, such as moving forward/backward in time or flying backwards, are also associated with increased risk of discomfort (Kolasinski).

Maneuver intensity (aggressive, dynamic, or violent maneuvering) has been implicated in SS, both in flight simulators [41, 63] and automobile simulators [19]. Also, the height above terrain at which pilots fly has been shown to vary inversely with discomfort level [16, 26, 33, 63]. Flying close to the ground (nap of the earth) causes more SS than flying at altitude. This is usually explained in terms of greater perception of visual flow, caused by greater visual detail or density, at lower height above terrain. Degree of control has been associated with increased susceptibility to SS [33, 48, 54]. The pilot in control of the simulator tends to report less discomfort than a passive passenger. Finally, head movements increase susceptibility to SS [26, 33, 41, 54]. This last point has long been a part of simulator-trainee lore. Participants, who find themselves vulnerable to SS, quickly learn to keep their heads stationary.

9.0 SIMULATOR SICKNESS, PERFORMANCE, AND TRAINING

9.1 Performance

Does SS harm the flight performance of experienced aviators while in the simulator? Does exposure to a simulator temporarily harm the cognitive, perceptual, or psychomotor performance of the participants? These are not subjects that have received a large amount of research attention.

Silverman and Slaughter [57] stated that 67 percent of the helicopter pilots in their experiment reported modifying their flight control inputs at some point during the simulator sessions to alleviate the symptoms of SS. Pilots reported that they "slowed control inputs" or "transferred controls" or "closed my eyes during rapid aircraft movements" (p. 16). Uliano et al. [61] had 25 experienced male helicopter pilots perform a series of tasks in the VTOL simulator. All pilots were to perform both an air taxi task and a slalom task according to prescribed standards. Performance in executing these tasks to standards was measured in three spatial dimensions (x, y, z). The authors found that there was a statistically significant negative correlation between the amount of SS reported and performance on the air taxi task. Specifically, the sicker were the aviators, the greater the percentage of time they flew out of tolerance in x, y, or z. The authors did not find a statistically significant relationship for the slalom task. Warner et al. [62] assessed 24 pilots flying two F-16 flight simulators through a challenging 50-minute course. They collected 18 objective measures of piloting performance (e.g., airspeed limits, height above ground level, etc.). These they correlated with SSQ scores. The authors found no consistent relationship between SS scores and piloting performance.

As part of their larger survey of Navy simulators Kennedy et al. [23] performed tests of cognitive, perceptual, and psychomotor capabilities. Three tests (Pattern Comparison, Grammatical Reasoning, Speed of Tapping) were administered both before and immediately after simulator exposure.

> Pre- versus post-performance changes were studied in only six different simulators. In no simulator were group performances poorer after exposure, and indeed, most changes showed learning effects from the first (pre) to the second (post) session. Based on interpolations from other experiments on non-pilot subjects, these changes appear within the range of improvements due to practice which are to be expected over two sessions. (Kennedy et al., [23] 5)

Kennedy, Fowlkes, et al. [28] measured performance on three tasks (Pattern Comparison, Grammatical Reasoning, Finger Tapping) both before and after simulator exposure for 411 aviators engaged in simulator-based training. These data were compared to that from a control group of 16 aviators who were not exposed to a simulator between the first (pre) and second (post) test. Both groups showed improvement (a practice effect) from the pre-test to the post-test for all three tasks. However, the improvement shown by the control group was greater than that shown by the simulator-exposed group. This was a small, but statistically significant, difference. In other words, the simulator exposure attenuated the size of the practice effect for the simulator group. Uliano et al. [61] tested 25 experienced male helicopter pilots on a grammatical reasoning task both before and after a 40-minute simulator flight. They reported that there was no statistically significant effect of the simulator flight on performance of the grammatical reasoning task.

Based on the limited evidence that exists, it appears that simulator exposure has little or no effect on the cognitive, perceptual, or psychomotor abilities of aviators. These results are consistent with a larger set of results from the MS literature.

9.2 Training

With the exception of theme parks, simulators are used for training important and often dangerous skills – such as flying a helicopter or driving a tank. Does SS harm this training? For anyone who has experienced simulator-induced discomfort, it certainly appears reasonable to suggest that SS may interfere with training. But does it? What is the evidence?

The fear that SS would limit the usefulness of simulators for flight training has been in existence since the very beginning [44, 45]. In fact, Miller and Goodson reported that use of the device they evaluated was

discontinued. Recall also that two of McCauley's four points concerned this issue [41]. He warned of compromised training and decreased simulator use caused by SS.

When researchers review the literature of SS, the possibility of compromised training and/or decreased simulator use is a common feature. At least 15 times between 1986 and 1997 researchers have mentioned this potential problem of simulator-based training [7, 9, 10, 23, 25, 27, 31, 33, 34, 36, 38, 56, 48, 63, 61] goes farther than other reviewers, however, by describing some of the evidence concerning SS and training.

> Although studies indicate that sickness can occur, little – if any – research has investigated whether such sickness has an impact on training effectiveness. (Kolasinski, [34], p. 151)

Given the primacy of this issue since 1958, it is remarkable how little empirical evidence there is on the subject. Chappelow [8] administered questionnaires to 271 Royal Air Force pilots training in either of two air combat simulators. Respondents who had reported sickness symptoms were asked to assess the effect of the experience on their willingness to use the simulator in the future. A total of 214 pilots answered this question. Four percent (4%) reported that the experience decreased their willingness to use the simulator again. Sixty-eight percent (68%) responded that it had no influence. Twenty-eight percent (28%) stated that the experience increased their willingness to use the simulator again, because they said it provided good training and was fun to operate.

Gower and Fowlkes [14] assessed the effect of SS on training by asking their sample of AH-1 pilots whether simulator-induced discomfort hampers training. They found two related results. First, there was a statistically significant positive correlation between SSQ scores and agreement with the statement that "discomfort hampers training." That is, the aviators who reported the most SS were more likely to agree that discomfort harms training. Second, only 8 percent of their sample agreed, "discomfort hampers training." Four percent (4%) were neutral on the question. Eighty-eight percent (88%) disagreed with the statement. It should be noted that these results were the self-reported opinions of Army aviators. No grades, test results, set-backs, training hours required, or other performance measures were presented to show in an objective fashion that, in fact, those participants experiencing more discomfort learned less than their non-sick counterparts.

Gower and Fowlkes [15] asked the same questions of their sample of UH-60 pilots and found the same pattern of results. First, there was a statistically significant positive correlation between SSQ scores and agreement with the statement that "discomfort hampers training." Second, this was the opinion of a small minority of their sample. Only 1 person (1%) of the 86 who answered this question agreed that discomfort disrupts training. Fifteen percent (15%) were neutral. Eighty-four percent (84%) disagreed with the statement. Again, no data on performance during training were collected that would bear on the issue of SS and amount learned.

Gower et al. [16] found the same pattern of results with their sample of helicopter pilots training in the CH-47 flight simulator. There was a significant positive correlation between SSQ scores and agreement with the statement that "discomfort hampers training." Again, only 1 person (1.5%) agreed with the statement. Two people were neutral (2.9%). Of the total of 68 responses to this question, 65 (95.6%) disagreed with the statement. Finally, as before, no performance data were presented as to SS and amount learned during training.

The results of these four questionnaire studies are clear. The vast majority of the aviators surveyed stated that the discomfort-producing potential of the devices did not detract from the training provided. However, a small minority of aviators – those experiencing the most sickness – held the opposite opinion. Given the centrality of this issue for simulator-based training, more research should be undertaken. Measures of performance in learning the required program of instruction should be correlated with measures of SS such as the SSQ.

In agreement with the quote from Kolasinski [34] above, the present author knows of no published research devoted to this question.

10.0 TREATMENT

As with MS, the surest treatment for SS is simple adaptation. Nearly everyone will adapt to a particular simulator eventually. To aid adaptation to a new simulator, aviators should begin with brief simulator hops, flying gentle maneuvers, with subsequent hops separated by one-day intervals (NTSC, 1988). In this context, “brief” means less than one hour, with breaks as needed. The maximum duration of any simulator session should never exceed two hours. Several other guidelines exist and will be described later in this report.

For those pilots who cannot adapt to a simulator, “… anti-motion sickness medication may be considered for the simulator period” (Crowley,[9], p. 357). Drugs previously used to control the symptoms of MS, such as hyoscine hydrobromide and dimenhydrinate (Dramamine), have also proven effective for relief of SS [3, 52, 53]. In the world of flight training, it is no secret that some aviators with a history of discomfort self-medicate with MS drugs prior to a simulator session. However, no drug can reduce the occurrence of SS for everyone. Further, every drug has side effects. For example, scopolamine administered as a treatment for SS is known to have side effects that could negatively affect learning [9]. An aviator with severe, intractable SS should visit his or her flight surgeon.

11.0 THEORY

SS is a form of MS. The two major theories that exist to explain MS are also used to explain SS. By far the more common is the sensory conflict theory [3, 50, 51, 52]. Virtually all research reports mention the sensory conflict theory by one of its names. Most authors employ it in the explication of their results. Early examples of how this theory has been applied to SS can be found in Kennedy and Frank [29], McCauley [41], and Reason and Brand [52]. The major competitor is the postural instability theory [54, 58, 59]. For a more detailed description of these two theories please see the discussion presented in the Motion Sickness section above.

11.1 Sensory Conflict Theory

The sensory conflict (SC) theory states that sensory inputs from the eyes, semicircular canals, otoliths, proprioceptors, and somatosensors are provided in parallel both to a neural store of past sensory patterns of spatial movement and to a comparator unit. This comparator unit compares the present pattern of motion information with that pattern expected based on prior motion history and stored in the neural store. A mismatch between the current pattern and the stored pattern generates a mismatch signal. This mismatch signal initiates both SS and the process of adaptation.

According to the SC theory, when an aviator is operating a new simulator the pattern of motion information presented by the senses is at variance with past experience in the flight environment. This conflict between the current sensory pattern and that pattern expected based upon past experience causes SS. That is, there is a conflict between the current novel motion environment and past experience. However, with continued sessions operating the device the relative mismatch between current pattern and stored patterns decreases until one has adapted. Flight simulators attempt to simulate flight – that is, to trick the human perceptual system. However, no device can perfectly simulate all the physical forces of flight. It is this inability to simulate flight perfectly that causes SS in experienced aviators.

However, one need not be an aviator to know the discomfort of SS. Anyone with a normal vestibular system is susceptible to SS when operating a novel motion simulator. The key concept is the mismatch between the novel motion environment (the current pattern of sensory stimulation in the simulator) and prior motion history (the patterns of sensory stimulation resident in the neural store). As the reader can see, the SC theory explains SS in exactly the same fashion it explains MS – only the motion environment has changed.

11.2 Postural Instability Theory

The PI theory notes that sickness-producing situations are characterized by their unfamiliarity to the participant. This unfamiliarity sometimes leads to an inability of the participant to maintain postural control. It is this postural instability that causes the discomfort – until the participant adapts. That is, a prolonged exposure to a novel motion environment causes postural instability that precedes and causes the sickness.

PI theory states that there are individual differences in postural stability. Further, an imposed motion presented by a simulator can induce postural instability. The interaction of the body's natural oscillation with the imposed oscillation created by the simulator leads to a form of wave interference effect that causes postural instability. This instability is the proximate cause of SS. Experimental evidence in support of this theory – from participants exposed to simulated motion – has been reported [58, 59]. The PI theory explains SS in exactly the same fashion it explains MS – only the nature of the novel motion environment has changed.

11.3 SS, Age, and Theory

The SC theory and the PI theory make different predictions in some instances. A few examples of these differences are presented earlier in this report in the Motion Sickness section. One issue on which these two competing theories make diametrically opposite predictions concerns the effect of age on susceptibility to SS.

The SC theory states that MS in all its forms must decline with age after about age 12. The reasons for this are that life experiences provide the neural store with a wealth of prior sensorimotor patterns of motion memories and also that receptivity (the strength of the mismatch) declines with age. The SC theory predicts that SS will decline with age. However when research shows that SS increases with age, these results are dismissed as being the product of a confounding with flight experience. Age and flight experience are strongly correlated among pilots. The SC theory predicts that with increasing flight hours the relative mismatch between the sensorimotor pattern of aircraft flight and that of simulator "flight" will be greater and will, therefore, engender more SS. However, this interpretation only exists because the overwhelming majority of simulator research has taken place in the world of aviator training – a world where older aviators are also more experienced aviators. The SC theory would have to predict that a large sample of adult non-aviators of widely different ages would show *decreasing* SS with increasing age.

The PI theory would have to make exactly the opposite prediction. Unlike the SC theory, the PI theory is stated in a way that allows it to be scientifically tested and falsified. According to this theory, SS is caused by postural instability. Postural stability among adults is known to decline with increasing age (e.g., Kane et al., [22]; Lyon, [39]). Therefore, PI theory would predict that a large sample of adult non-aviators of widely different ages would show *increasing* SS with increasing age. Further, within any age cohort this theory predicts that greater instability will be associated with greater SS. So this theory not only makes a general prediction concerning age, but also makes a prediction concerning specific aged adults.

It is not an everyday occurrence in science that two competing theories make precisely opposite predictions. The test suggested above could add to the theoretical understanding of all motion sickness phenomena. Again,

the most difficult parts of this experiment would be to gain access both to a large sample of adult non-aviators, as well as to the simulator itself.

12.0 GUIDELINES FOR REDUCING SIMULATOR SICKNESS AND RISKS FROM AFTEREFFECTS

Several authors have taken the time to publish guidelines in an effort to reduce the rate of SS among trainee populations [6, 10, 25, 33, 38, 41, 47, 63]. Arguably the most thorough set of guidelines are those by Kennedy et al. and Wright. These authors not only provide guidelines, but also explain the reasons for the guidelines and the evidence supporting them. If the reader does not have time for a detailed presentation, the best and most entertaining single source is the field manual published by the Naval Training Systems Center (NTSC).

The temptation to include guidelines of one's own is almost impossible for authors to resist. This is not only because SS is so discomforting to one's trainees, but also because some policies and procedures are clearly better than others. So in the interests of preventing future discomfort the current author will list some suggestions. This is by no means an exhaustive listing.

12.1 General Rules

- Simulator flights should not be scheduled on the same day as aircraft flights.
- Arrive for simulator training in your usual state of health and fitness.
  - Avoid fatigue or sleep loss, hangover, upset stomach, head colds, ear infections, ear blockages, upper respiratory illness, medications, and alcohol.
  - If you have been sick recently and are not fully recovered, reschedule your simulator training.
- Persons who are new to the simulator, or who have not operated it in months, are at risk.
- Do not schedule simulator sessions for greater than two hours for any reason.
  - Use breaks, time-outs extensively.
  - The more nauseogenic the session, the shorter the session should be.
    - Aggressive, violent maneuvers, near ground level, are more nauseogenic than high, straight-and-level flight.
- Adaptation is one of the most potent fixes for SS.
  - In order to optimize adaptation, there should be a minimum of one day between simulator sessions, and a maximum of seven days.
  - Begin with short sessions, using non-nauseogenic maneuvers.
  - Minimize rapid gain and loss in altitude; minimize abrupt or continued roll; minimize porpoising.
  - Fly the most provocative tasks at the end of the session.
- Minimize head movement, particularly when new or dynamic maneuvers are being trained.
- Tell your instructor if you are experiencing discomfort.

- The instructor should avoid, or at least minimize, use of the freeze command.
  - Have the pilot close his or her eyes before using the freeze command.
  - Have the pilot close his or her eyes before resetting the simulator to another location. Or, turn off visual display before reset.
- The instructor should turn off visual display and turn on cabin lights before asking the pilot to exit the simulator.
- The instructor should decrease the field of view (turn off side displays) during early sessions, nauseogenic maneuvers, or if the pilot shows any symptoms of discomfort.
  - Or, go on instruments at the first sign of discomfort.
- Avoid high-risk activities for at least 12 hours after simulator training.
  - High-risk activities include flying, climbing, driving, riding motorcycles, riding bicycles, or diving.
  - Use handrails to help maintain balance when going up or down stairs.

13.0 SUGGESTIONS FOR FUTURE RESEARCH

This review has uncovered at least two areas where further research into the subject of SS is clearly warranted.

- *The effect of SS on training.* As this review has shown repeatedly, one of the key arguments offered for studying SS is the potential for compromised training. However, there is virtually no evidence to support this argument. There is no evidence showing a statistically significant and substantial difference in the amount learned as a function of reported level of discomfort. Given that most simulator-based research takes place at aviation training sites, this oversight is particularly curious. This research topic is important and should be examined in a quantitative empirical fashion.
- *The effect of chronological age on SS.* Does increasing adult age make one more susceptible to SS or less susceptible? Are older aviators more susceptible to SS because they are older, because they have more flight experience, or some combination of both? Perhaps the best reason to investigate this subject parametrically is because the two leading theories of SS make precisely opposite predictions. The SC theory predicts that SS will decrease with increasing chronological age. The PI theory predicts that SS will increase with increasing chronological age. Thus, performing this research has the added benefit of increasing our theoretical understanding of SS.

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